University of Groningen

From the grid to the smart grid, topologically

Pagani, G. A.; Aiello, M.

Published in:
Physica A: Statistical Mechanics and its Applications

DOI:
[10.1016/j.physa.2015.12.080](https://doi.org/10.1016/j.physa.2015.12.080)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2016

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Pagani, G. A., & Aiello, M. (2016). From the grid to the smart grid, topologically. *Physica A: Statistical Mechanics and its Applications*, 449(5), 160-175. <https://doi.org/10.1016/j.physa.2015.12.080>

Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: <https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment>.

Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

From the grid to the smart grid, topologically

Giuliano Andrea Pagani*, Marco Aiello

Distributed Systems Group, Johann Bernoulli Institute for Mathematics and Computer Science, University of Groningen, Groningen, The Netherlands

HIGHLIGHTS

- Network evolution for Smart Grid.
- Complex Network for Power Grid design.
- Effects of topology on the cost of electricity distribution.
- Strategy comparison for link addition in networks.

ARTICLE INFO

Article history:

Received 11 February 2014

Received in revised form 12 June 2015

Available online 30 December 2015

Keywords:

Power grid

Distribution grid

Smart grid

Complex network analysis

Decision support systems

ABSTRACT

In its more visionary acceptance, the smart grid is a model of energy management in which the users are engaged in producing energy as well as consuming it, while having information systems fully aware of the energy demand-response of the network and of dynamically varying prices. A natural question is then: to make the smart grid a reality will the distribution grid have to be upgraded? We assume a positive answer to the question and we consider the lower layers of medium and low voltage to be the most affected by the change. In our previous work, we analyzed samples of the Dutch distribution grid (Pagani and Aiello, 2011) and we considered possible evolutions of these using synthetic topologies modeled after studies of complex systems in other technological domains (Pagani and Aiello, 2014). In this paper, we take an extra important step by defining a methodology for evolving any existing physical power grid to a good smart grid model, thus laying the foundations for a decision support system for utilities and governmental organizations. In doing so, we consider several possible evolution strategies and apply them to the Dutch distribution grid. We show how increasing connectivity is beneficial in realizing more efficient and reliable networks. Our proposal is topological in nature, enhanced with economic considerations of the costs of such evolutions in terms of cabling expenses and economic benefits of evolving the grid.

© 2015 Elsevier B.V. All rights reserved.

1. Introduction

The power grid traces its roots in the late 18th century. Then, it involved large production facilities and a hierarchical grid composed of high (transmission), medium and low voltage (distribution) grids to transport and distribute the power to the end users. Traditionally, the power industry has been a sector characterized by being a (state-owned) monopoly. Nowadays there is a strong trend for innovation driven by the need of making the infrastructure more reliable, open, and to accommodate for new technology, both in term of renewable energy generation and digital infrastructure. The technological

* Corresponding author.

E-mail addresses: g.a.pagani@rug.nl (G.A. Pagani), m.aiello@rug.nl (M. Aiello).

Fig. 1. Engineering process for medium and low voltage grid optimized for prosumer-based energy exchange.

innovation and the political pressure for a new power grid often go under the name of *smart grid*, which though has no unique definition [1]. One of the prominent aspects that the smart grid will enable is the participation of small producers in the energy distribution. It is already possible today for an end user to produce energy with small-scale units such as solar panels, small wind turbines, and micro-Combined Heat Power generators (mCHP). The energy produced is sold back to the local energy distributor. More efficiency and perhaps sustainability can be achieved if the producers would have access to an open energy market where they can auction their over-production and buy energy in a truly competitive market. Local energy production and distribution will change the traditional way power systems have been considered so far: the low voltage layer of the grid will go from being a passive layer, to an active segment with multi-directional energy flows. This trend will inevitably affect the physical structure of the medium and low voltage grid, also topologically. The reason for this is that the cost of distribution will be of primary importance in enabling or repressing a local market of energy.

Assuming the need for an enhancement of the physical low voltage grid, our aim is to realize a decision support system to guide distribution operators, policy makers, and utilities to evaluate scenarios of network improvement and to realize more efficient distribution grids. We propose a process to analyze, design, and adapt existing distribution networks based on statistical models of the power grid as a weighted network. A visual representation of the process is presented in Fig. 1. In the figure, several phases and inputs are considered to plan the evolution of the infrastructure where local energy exchange is the guiding principle. It starts with a pre-processing phase where the input data of the grid is converted into a graph; the output of this initial phase is a power grid graph. The following phase consists of the analysis of the topological properties characterizing the graph. The output of this phase consists of a set of values representing the metrics related to the power grid that influence the price of electricity (α and β metrics in the figure). The process continues with the generation of a network model. The number of nodes and edges of this reference model are provided according to the targets for the cost-related parameters (α and β) and the will to invest of the stakeholders. Based on the theoretical model identified, the physical network under assessment is then fitted into a topological structure similar to the one of the model. Several solutions are provided that differ in the topology and the economic efficiency of power distribution. All these solutions are then input to an interactive module that presents the benefits/costs of the evolution of the network; an expert is involved in the selection of the evolution to be implemented among the most promising candidates built by the computer. Once the decision is made, the adaptation of the physical grid can be planned in details following traditional power system engineering techniques.

We covered the initial steps of the process in our previous works. In Ref. [2], we performed a topological analysis of samples from the Dutch medium and low voltage power grids. We developed a set of metrics based on weighted topological properties to assess the influence on the cost of electricity distribution for a set of real Dutch medium and low voltage Grids. In the following Ref. [3], we evaluated known (reference) models of technological networks to evaluate how they would perform for local energy exchange. We found that an increase in connectivity from the current value of average degree of two to higher values such as four and higher is beneficial in improving the efficiency and reliability of the network. We also found that the small-world model with average degree $\langle k \rangle \approx 4$ provides a very promising compromise between performance improvement and the thrift in the realization (i.e., cost for cabling). Although the generation from scratch of a network topology is interesting from a modeling and theoretical perspective, it is not common to design a distribution grid from scratch. In this paper, we take a practical step in evaluating how to evolve the current distribution grid to a more interconnected network taking into account the existing network and the physical constraints. We keep the basis of our statistical approach to weighted network evolution and apply it to Dutch samples of the medium voltage networks. We not only assess the benefits in terms of pure topology, but also the costs for cabling of the evolved networks, and the benefit in terms of costs of electricity distribution. There are several novelties with this approach. First, techniques typical of complex network analysis are employed as design tools; second, given that the smart grid mostly concerns the distribution grid, we focus on these networks which are topologically quite different from the high voltage grids typically studied in the literature [4]; third, we provide the basics for a decision support system that works in the large and not for individual subcomponents of the grid, as is typical for power system engineering tools.

The rest of the paper is organized as follows. We open by describing the motivations and the need that drive an upgrade of the grid (Section 2), then we dive into the evolution strategies followed in upgrading the samples of the distribution grid

(Section 3). The analysis and an overall discussion comparing the evolution strategies is provided in Section 4. Section 5 takes into account benefits and costs of evolution of the Dutch grid samples. Section 6 reviews the main approaches presented in the literature of electrical grid design and evolution, while Section 7 provides final considerations.

2. The need for a new grid

In 2003 all the major players in the American power system met and agreed on the aging of the US electrical infrastructure, in particular, in terms of inefficiency and safety [5]. Experts envisioned the ingredients that today we would ascribe to what a Smart Grid should be. The main focus of that meeting was the high voltage power grid, but the same conclusion could be drawn for the low voltage grid. Actually, the high voltage grid is already a quite “smart grid” with supervisory control, data acquisition (SCADA), and energy management systems (EMS). On the other hand, the distribution infrastructure is usually neglected given its mainly passive role and typically not equipped with ICT systems that we related to smartness [6]. A key aspect is that the medium and low voltage grid are the ones that have to accommodate an increasing number of renewable sources [7]. In other terms, one is witnessing a shift in focus in the research on power systems from the higher to the lower voltage layers. Challenges of reliability of the high voltage infrastructure seem to have been mostly addressed, while it is not clear how the medium and low voltage grids can manage a multidirectional flow operation and the inclusion of distributed generation thus posing a number of novel and challenging research questions.

Such requirement for the evolution in the Distribution grid is driven by two inter-related aspects: on the one hand, the pressure for unbundling the energy sector, and, on the other hand, the availability and affordability of small-scale renewable-based energy production units. Unbundling entails the breaking of monopolies in the energy sector and the installing of competition among stakeholders. The underlying aim is to provide better services and lower tariffs for the end-users [8]. At the extreme of the unbundling idea is the vision for which potentially everybody can produce energy and participate as a seller on a free energy market [9,10]. In such a context, with many small-scale producers and still without an efficient and cheap energy storage technology, a local energy exchange at the neighborhood or municipal level between end-users is foreseeable and desirable, though needing appropriate infrastructure.

A future with plenty of prosumers that produce energy and sell or share it at the level of neighborhoods will affect the distribution grid. The change from a passive-only grid to a Smart grid will require to rethink the role of the medium and low voltage grid [11]. In our study of considering how to evolve or adapt the current distribution grid to a Smart grid, we resort to Complex Network Analysis not only to analyze the existing infrastructure, but also to drive the design of the next generation grid. *Complex Network Analysis (CNA)* is a branch of Graph Theory taking its root in the early studies of Erdős and Rényi [12] on random graphs and considering statistical structural properties of evolving very large graphs. Taking its root in the past, complex network analysis is a relatively young field of research. The first systematic studies that appeared in the late 1990s [13] have the goal of looking at the properties of large networks with a complex systems behavior.

3. Evolving the current power grid

We start by taking samples of medium voltage from the Dutch power grid.¹ Table 1 summarizes the main facts of these samples (described in detail in Ref. [2]). The samples belong to the distribution grid of the Northern region of the Netherlands. The data have been provided courtesy of Enexis B.V., the Netherlands. The medium voltage samples belong to villages or cities in the Groningen region, while the low voltage ones are just small sub-sections involving just a limited amount of buildings in few streets of villages or cities of the same region. The first column represents the identifier of the sample, column two and three provide the *order* (# of vertexes) and *size* (# of edges) of the sample; these two values are used to compute the average degree that is shown in the fourth column. Column five gives an impression on the effort to reach one node from any other in the network through the characteristic path length. A measure of local clustering is given in column six with the clustering coefficient metric. Robustness of the network to failures concerning its connectivity (Rob_N) is evaluated by computing its connectivity. In particular, the *order* of the maximal connected component (MCC) of the graph is computed when 20% of the nodes of the graph are removed and the ratio is evaluated to the initial *order*. The removal of nodes are performed following a random policy and a targeted one by focusing on the nodes with higher degree first. The average between the two values gives an overall estimation of the disruption of the network (column seven). Column eight deals with the redundancy of paths (APL_{10th}), which takes into account the increase in the average path length when the 10th shortest path is computed. This metric provides a measure of the additional effort required to exploit alternative paths different than the optimal one. Columns nine through eleven are related to betweenness, that is to the nodes that are involved in the shortest paths. The quantities are average betweenness (column nine), the ratio among average betweenness and *order* of the graph (column ten), and the coefficient of variation of betweenness (ratio between standard deviation and the average). Usually, low voltage and medium voltage networks have a low average node degree: about $\langle k \rangle \approx 2$. Besides the difference in the *order* and *size* between the two types of networks (generally the medium voltage network samples are bigger), the low voltage samples have a null clustering coefficient, while the medium voltage networks present a small,

¹ For the description of the modeling of the power grid as a graph and the basic graph theory properties we refer to Refs. [4,14,15].

Table 1

Topological statistics for medium voltage samples from the Northern Netherlands grid.

ID	Order	Size	Avg. d	CPL	γ	Rob.	10th path	Avg. betw.	Avg. betw./order	Coeff. variation
1	444	486	2.189	10.858	0.00537	0.185	20.173	4329.054	9.750	2.050
2	472	506	2.144	17.174	0.01360	0.121	24.717	5087.728	10.779	1.704
3	238	245	2.059	11.580	0.00000	0.153	33.405	1910.757	8.028	1.566
4	263	288	2.190	12.311	0.01118	0.179	21.517	1237.711	4.706	1.517
5	217	229	2.111	10.241	0.00140	0.187	21.740	3169.571	14.606	1.743
6	191	207	2.168	8.990	0.00296	0.211	17.487	3870.640	20.265	1.432
7	884	1059	2.396	9.527	0.00494	0.297	12.833	7755.542	8.773	2.875
8	366	382	2.087	14.546	0.00000	0.142	25.262	5136.520	14.034	1.691
9	218	232	2.128	10.915	0.00000	0.201	24.773	1244.663	5.709	1.544
10	201	204	2.030	15.257	0.00166	0.138	33.273	3613.691	17.979	1.173
11	202	213	2.109	12.891	0.00140	0.160	26.463	2690.183	13.318	1.331
12	464	499	2.151	12.703	0.00036	0.178	18.051	3424.602	7.381	1.687

but at least significant, value. This difference is explained in the different topology and purpose of the networks: a radial structure with no clustering to distribute electricity to the end-users (low voltage) and a more meshed structure for the medium voltage that shows small clustering values.

Next, we consider evolutions starting from the Dutch samples, that is, adding cables according to several strategies of network growth. We break the evolutions into four groups of edge growth: increments of 25%, 50%, 75%, and 100%. The choice of stopping at 100% is performed based on the results of Ref. [3], where it is shown that an average node degree of $\langle k \rangle = 4$ has the right balance of improved network qualities and costs of network evolution. We consider several strategies for evolving the graph by adding more links, namely:

- **Assortativity.** A network is assortative if nodes having similar characteristics or properties are connected one another [16]. The property we consider is that of node degree and then take two strategies:
 - **high degree** nodes are connected one another. The process starts with considering a set of nodes with the highest equal node degree and connect them together. The process goes on considering the next set of nodes with equal high degree in the order of rank and so on.
 - **low degree** nodes are connected one another. The process goes on as for the high degree strategy, but nodes are linked starting from the couples with lowest degree.
- **Dissortativity** is the opposite of assortativity, that is, a network is dissortative if nodes having different characteristics or properties are connected together. Following this strategy, nodes with highest node degree are linked to nodes with lowest node degree.
- **Triangle closure** is based on the principle of increasing the clustering coefficient of the network. At each step, a node is selected at random and for each pair of its neighbors an edge is added between them, if not already present.
- **Least distance** gives priority to the connection of nodes that are geographically closer to each other. This strategy can minimize the costs of cabling since such costs are directly proportional to the length of cables.
- **Random** is based on the random selection of nodes to attach edges. At each step of the growth process, a pair of distinct nodes are randomly selected and an edge between them is added.

For every strategy, if two nodes already have an edge that connects them the edge is not added and the evolution strategy continues. In fact, in the graph models we only allow a single edge between a pair of nodes.

4. From the current distribution infrastructure to the smart grid

We evolve physical networks according the strategies described in Section 3 and analyze the obtained graphs according to a set of metrics that provide a view of efficiency of the whole network and its adequacy for local energy distribution. Such metrics consider the path length properties of the graph, the presence of ‘local cliques’ (i.e., clustering coefficient), the presence of critical nodes that manage the majority of paths (i.e., betweenness). We also take into account the robustness to failures with respect to network connectivity (Rob_N) and the redundancy of paths (APL_{10th}) different from the optimal one. To study the effects of the evolution, we implement the strategies using the JAVA graph library JGraphT (<http://www.jgrapht.org/>). The same library suite has been used to compute the metrics just described. The only metric computed with a different software library is the ‘betweenness’ one. For this computation, the Stanford Network Analysis Project (SNAP—<http://snap.stanford.edu/>) software library has been used since it leverages on the algorithm developed by Brandes [17] with optimal performance. To perform the generation and computation of the metrics, we used a standard PC with Intel Core2 Quad CPU Q9400 2.66 GHz with 4 GB RAM. The Operating system is based on the Linux kernel 2.6.32 with a 4.4.3 GCC compiler and JAVA framework 1.6. The versions of JGraphT and SNAP software libraries used are respectively v0.8.1 and v10.10.01. Next, we present the results of the generation and metrics evaluation.

Table 2
Metrics summary.

Metric	Efficiency	Resilience	Robustness
CPL	✓		
CC	✓		
Avg. betweenness		✓	
Betw. coeff. of variation		✓	
Rob_N			✓
APL_{10th}	✓	✓	

4.1. Network metrics

To assess the suitability of network topologies for the local energy exchange, we consider requirements and metrics coming from traditional CNA metrics and from the results obtained in our previous analysis of medium and low voltage Power Grids [2,3]. The novelty resides in defining bounds for the values of such metrics and evaluating the satisfaction of such metrics by the evolved networks.

When considering efficiency, resilience, and robustness of a power system the following metrics provide valuable indications.

- (A) *Characteristic Path Length (CPL) lower or equal to the natural logarithm of order of graph: $CPL \leq \ln(N)$.* The requirement deals with providing, generally, a limited path when moving from one node to another. In the grid this provides for a network with limited losses in the paths used to transfer energy from one node to another.
- (B) *Clustering Coefficient (CC) which is 5 times higher than a corresponding random graph with same order and size: $CC \geq 5 \times CC_{RG}$.* Watts and Strogatz [18] show that small-world networks have clustering coefficient such that $CC \gg CC_{RG}$. Here we require a similar condition, although less strong by putting a constant value of 5. This requirement is proposed in order to guarantee a local clustering among nodes since it is more likely that energy exchanges occur at a very local scale (e.g., neighborhood) when small-scale distributed energy resources are highly implemented.
- (C) *Betweenness-related requirements: (1) A low value for average betweenness in terms of order of the graph $\bar{v} = \frac{\bar{\sigma}}{N}$, where $\bar{\sigma}$ is the average betweenness of the graph and N is the order of the graph. For the Internet Vázquez et al. [19] have found for this metric $\bar{v} \approx 2.5$. Internet has proved successful to tolerate failures and attacks [20], therefore we require a similar value for this metric for the future grid. (2) A coefficient of variation for betweenness $c_v = \frac{s}{\bar{x}} < 1$ where s is the sample standard deviation and $\bar{x}$ is the sample mean of betweenness. Distributions with $c_v < 1$ are known as low-variance ones.*

The above two requirements are generally considered to provide network resilience by limiting the number of critical nodes that have a high number of minimal paths traversing them. These properties provide distributions of shortest paths which are more uniform among all nodes.

- (D) *An index for robustness such that $Rob_N \geq 0.45$.* Robustness is evaluated with the random removal strategy and the node-degree-based removal of nodes by computing the average of the *order* of maximal connected component between the two situations when the 20% of the nodes of the original graph are removed. It can be written as: $Rob_N = \frac{|MCC_{Random20\%}| + |MCC_{NodeDegree20\%}|}{2}$. Such a requirement is about double the value observed for current medium voltage and 33% more for low voltage samples [2].
- (E) *A measure of the cost related to the redundancy of paths available in the network: $APL_{10th} \leq 2 \times CPL$.* With this metric we consider the cost of having redundant paths available between nodes. In particular, we evaluate the 10th shortest path (i.e., the shortest path when the nine best ones are not considered) by averaging the values obtained from a random sample of the nodes in the network.

We classify the above quantitative metrics into three macro categories with respect to how they affect the power grid and measure its goodness from a topological point of view: efficiency in the transfer of energy, resilience in providing alternative paths if part of the network is compromised/congested and robustness to failures for network connectivity. Table 2 summarizes the property each metric assesses. Each metric gives a specific contribution and all the metrics together cover all the properties a smart grid infrastructure should have.

To determine which strategy, from a topological point of view, is more rewarding and provides the higher benefits one needs to compare the metrics obtained with the various evolution strategies. If determining a “best” strategy is unreasonable, one should aim at identifying trade-offs between one strategy compared to another one. We evaluate all the strategies considering average values over all the samples and considering the satisfaction of the topological metrics defined above.

4.2. Comparison of the evolution strategies for the medium voltage distribution grid

It is difficult, and perhaps even wrong, to establish “the winner” between the various evolution strategies proposed. Also because the improvement in the various phases of evolution are not linear. A strategy that scores best in one evolution step could result worse compared to another when more edges are added. Fig. 4(b) shows the trend in the evolution of the

Fig. 2. Stages of evolution of medium voltage sample #8 following least distance strategy.

robustness to targeted attacks towards high degree nodes following a triangle closure strategy, while Fig. 4(b) shows the trend in the evolution of the clustering coefficient for a dissortative strategy. One sees that in both cases the majority of the medium voltage samples do not show a consistent trend, while actually the metrics fluctuate during the edge addition process.

The addition of links is beneficial to the topological metrics analyzed and one might speculate that the optimal solution in order to minimize (or maximize) the metrics is to realize a completely connected network. With a real infrastructure such as the power grid this is unrealistic due to economic considerations, but also from a technical point of view (e.g., substations receiving thousand of connections). A visual representation of the evolution process obtained following the least distance strategy is shown in Fig. 2 and following the assortative high degree strategy is shown in Fig. 3.

Table 3 shows the comparison of the averages over all samples in each evolution step for the various evolution strategies. Take the triangle closure strategy, for instance, it is the one that at every step of the evolution process leads to the maximal values for the clustering coefficient, but it is also the one that has the worst results together with the least distance strategy for the metrics related to path length (characteristic path length and 10th redundant average path length). In addition, considering the robustness metric, the triangle closure offers the smallest improvements. Also considering the betweenness-related metrics, the triangle closure strategy results the worst compared to all the others with the second set of highest values for average betweenness and an increasing coefficient of variation. The same considerations apply to the least distance strategy that to a certain extent is very similar to the triangle closure one. This strategy is the worst concerning the path length, having a characteristic path length more than double than the best evolution strategy (i.e., random); the same also applies for the 10th redundant average path length. Concerning redundancy aspects at the end of the evolution process, the least distance strategy is the one (except for random) that have the best robustness results. In terms of metrics related to betweenness, the least distance strategy shows results that are even worse compared to the triangle closure one. Considering the high degree assortative evolution strategy the results show that, overall, it is the best evolution strategy in the first two steps of the evolution; in the first step it is even better than the random one (with the exception of robustness). Considering betweenness metrics, this strategy is second only to the random strategy one, with the exception

Fig. 3. Stages of evolution of medium voltage sample #8 following the assortative high degree strategy.

of coefficient of variation which is worse than all other metrics. In general, this is a good strategy of evolving the network especially concerning the path-related aspects, with just robustness that lacks compared to other evolution strategies. The assortative low degree strategy is not particularly appealing and it is outrun by the assortative high degree strategy in every metric except robustness and coefficient of variation of betweenness, therefore we do not find it particularly interesting for evolution purposes of the medium voltage networks. The dissortative strategy does not excel particularly in any of the metrics considered, however its values are quite fair, especially in the initial stage of the evolution. In particular, since the values of the metric do not improve particularly in the following steps of the evolution process, such evolution strategy could be used as a slightly more robust alternative compared to the assortative high degree in those scenario where the number of edges to be added is minimal and there is no need of special excellence in one topological parameter. When

Fig. 4. Non linear evolution of metrics for medium voltage samples.

Table 3

Comparison of evolution strategies for medium voltage network.

	Evolution step	CPL	γ	Rob.	10th red. path	Avg. bet.	Avg. bet./order	Coeff. var.
Assortative high degree	+25%	5.757	0.037	0.326	8.550	1682.845	4.744	2.258
	+50%	5.121	0.067	0.344	7.095	1369.399	4.100	2.259
	+75%	4.724	0.098	0.361	6.493	1245.963	3.799	2.147
	+100%	4.558	0.122	0.367	6.072	1226.062	3.717	1.904
Assortative low degree	+25%	6.404	0.045	0.358	9.503	1955.047	5.598	2.039
	+50%	6.320	0.090	0.408	8.492	1931.053	5.508	1.651
	+75%	6.261	0.109	0.482	8.149	1913.409	5.440	1.504
	+100%	6.172	0.121	0.496	8.014	1888.415	5.357	1.441
Triangle closure	+25%	10.761	0.165	0.257	14.559	2698.910	8.130	1.786
	+50%	9.504	0.288	0.321	11.680	2377.892	7.123	1.872
	+75%	8.482	0.388	0.341	10.053	2104.554	6.289	1.927
	+100%	7.618	0.483	0.384	8.997	1884.527	5.563	2.034
Dissortative	+25%	5.803	0.019	0.349	8.891	1727.708	4.949	2.433
	+50%	5.591	0.028	0.408	7.904	1645.824	4.710	1.953
	+75%	5.402	0.034	0.463	7.421	1594.361	4.532	1.739
	+100%	5.217	0.033	0.468	7.053	1559.650	4.418	1.613
Least distance	+25%	10.025	0.141	0.272	13.078	3044.817	9.042	1.703
	+50%	9.066	0.214	0.360	11.696	2789.684	8.127	1.744
	+75%	8.535	0.261	0.455	10.705	2646.133	7.652	1.788
	+100%	8.109	0.304	0.523	10.013	2525.651	7.275	1.807
Random	+25%	6.249	0.011	0.423	9.954	1785.946	5.265	1.194
	+50%	4.990	0.016	0.634	7.780	1378.933	3.998	1.074
	+75%	4.393	0.019	0.737	6.739	1178.359	3.394	0.964
	+100%	4.000	0.027	0.764	6.080	1044.279	2.988	0.881

enough connectivity is added, the evolution strategy that scores best compared to all the others for all the metrics, with the exception of the clustering coefficient metric, is the random one. It has already been noted by Casals et al. [21] that some randomness in the network is beneficial especially for aspects related to robustness. In our analysis we have the same general results, with characteristic path length about 4 and a 10th redundant average path length of just 6. In addition, the networks evolved according to this strategy are the most robust with a value higher than 0.7 when the maximal connectivity is reached. The same considerations apply for betweenness metrics. These obtain the best results when the connectivity is enhanced reaching a betweenness to order ratio smaller than three and a coefficient of variation below one at the last evolution step. However, it is difficult to propose a distribution provider to improve his grid in a random fashion, even if part of the weaknesses and inefficiencies come from the lack of such randomness. Considering rational and evolution strategies that come with a motivation we consider the strategy assortative high degree as the one that, by evaluating the various topological metrics only, scores best in the evolution tests that we have performed on the Dutch medium voltage Grids.

4.3. Parameter satisfaction for medium voltage networks

We now consider the satisfaction of the quantitative metrics described in Section 4.1 to analyze the appropriateness of synthetic topologies to improve the grid in reducing losses, facilitate local energy distribution, and increasing network

robustness. The satisfaction of these metrics provides topologies where the cost of electricity for the end-user are lower given that the metrics directly influence the cost of electricity distribution [2].

Assortative high degree. The assortative high degree evolution strategy satisfies the desired values for the metrics concerning the characteristic path length already from the second step of evolution for ten out of twelve samples. All samples satisfy the requirements over the redundant path. Considering the clustering coefficient, the majority of samples satisfies the requirement at the third step of evolution where seven samples have a $CC \geq 5 \times CC_{RG}$; in the final stage of evolution this metric is satisfied by all the samples except two. The real drawback of this metric is, as shown in the table, represented by the robustness that never reaches the goal of 0.45, but stops at around 0.37. The unsatisfaction of the metric is also present for betweenness ones: all samples are one unit larger even in the last step of evolution. In addition, the coefficient of variation never reaches the target for the samples at any stage of evolution.

Assortative low degree. The assortative low degree evolution strategy satisfies the desired values for the metrics concerning the clustering coefficient already from the second step of evolution with eleven out of twelve samples. All the samples satisfy the requirements over the redundant path already from the first step. Considering the clustering coefficient, the majority of samples satisfies the requirement at the second step of evolution where seven samples have a $CC \geq 5 \times CC_{RG}$; in the final stage of evolution this metric is satisfied by all the samples except one. This metric almost provides the satisfaction of the robustness requirement from the third step by having six samples fully satisfying it and three very close to the 0.45 threshold. The metrics concerning betweenness are not satisfied both for betweenness to *order* ratio and for the coefficient of variation which never reach the target for the samples at any stage of evolution.

Triangle closure. The triangle closure evolution strategy focuses on the clustering coefficient, therefore reaching the target already in the first step of the evolution. The evolved graphs do not only satisfy the requirement posed of having $CC \geq 5 \times CC_{RG}$, but also a more restrictive requirement of $CC \geq 10 \times CC_{RG}$ which can be considered the condition for satisfying the small-world requirement for this property cf. Ref. [18]. Concerning the path length properties, the characteristic path length is never lower than the logarithm of the *order* of the graph. The requirement over the 10th average path length is satisfied already from the first addition of edges. On all other requirements this strategy is weak. For robustness just few samples reach values around 0.4, while the majority is about 0.3 when the most of the edges are added. For metrics that involve betweenness, this evolution strategy scores poorly and never even close for any single sample to the target for both average betweenness to *order* ratio and for the coefficient of variation.

Dissortative node degree. The dissortative node degree strategy scores quite poorly. As mentioned before, this strategy does not excel in one specific metric, but all the metrics are slightly improved. Such aspects result in a limited crossing of the threshold for the desired values for the parameters. Only after the third evolution step the characteristic path length is almost satisfied: nine of the twelve samples reach the target, while one more reaches the target when even more edges are added. A similar condition is true for the robustness metric. In fact, six samples satisfy the target after the third step and other three are above the 0.4 value. The clustering coefficient is always well below the threshold, having values that often are just slightly higher than the clustering coefficient of a random graph with same *order* and *size*. The only metric fully satisfied is the one related to redundant paths in the network. While the metrics related to betweenness are not satisfied even at later stages of evolution.

Least distance. The results of the least distance strategy are similar to those of triangle closure. The clustering coefficient desiderata is reached already in the first step of the evolution. From the second step on, the evolved graphs do not only satisfy the requirement posed of having $CC \geq 5 \times CC_{RG}$, but also a more restrictive requirement of $CC \geq 10 \times CC_{RG}$ which can be considered the condition for satisfying the small-world requirement for this property cf. [18]. Concerning the path length properties, the characteristic path length is never lower than the logarithm of the *order* of the graph. However, the easy requirement related to the 10th average path length is satisfied already from the first addition of edges. Robustness is another positive note of this evolution strategy. From the third step on, the seven samples reach the 0.45 target and other three are close to 0.4; in the last step basically all the medium voltage evolved samples satisfy the desiderata. The situation is not so positive for betweenness related metrics since they score worse compared to the other strategies for both average betweenness to *order* ratio and for the coefficient of variation.

Random. The random evolution strategy is the one that satisfies most of the parameters already after the second evolution step. The metrics concerning the characteristic path length are satisfied basically already from the second step of evolution. The same applies to the redundant path whose goal is met already in the first evolution step. Robustness is really impressively achieved after the addition of 50% of more edges, with all the samples above the 0.45 threshold and the majority of them scoring even higher, above 0.6. The metrics related to betweenness, that usually fail for the other samples, are here met completely; e.g., the coefficient of variation after the third evolution stage has eight out the twelve samples meet the target. In addition, this evolution strategy is the one that also goes closer to the satisfaction of the betweenness to *order* ratio. The only problem of such a strategy is on the clustering coefficient side.

The random evolution strategy is the one that satisfies most of the requirements (three parameters fully satisfied and one nearly satisfied) already at the second stage of evolution and from the third step on, four requirements are fully satisfied. This strategy is in line with the findings of our previous work [3] where a small-world model was the best solution for modeling a smart grid topology. The addition of random edges goes into that direction: the network with the rational structure planned by the power engineers is modified by the addition of random links, thus in something between the rational topology and

Table 4
Parameter satisfaction.

Network level	Strategy	Optimality	Optimality reached at step
MV	Assortative HD	***	4
MV	Assortative LD	**	2
MV	Triangle closure	**	1
MV	Dissortative	*	1
MV	Least distance	***	4
MV	Random	****	3
LV	Assortative HD	**	3
LV	Assortative LD	**	4
LV	Triangle closure	**	3
LV	Dissortative	***	4
LV	Random	****	4

the fully random network. Other quite promising strategies are the assortative high degree and the least distance, but only after the number of edges doubles. Concerning the other strategies that have an evolution with a specific goal, those that satisfy most of the requirements are the assortative high degree and the least distance one. Both strategies satisfy three out of the six parameters, the difference being that the assortative one has good performance for the characteristic path length parameters, while the least distance strategy reaches the target for the robustness aspects. Therefore, these sub-optimal strategies could be used where such other requirements have higher priority.

A commonality between the evolution strategies for medium voltage and low voltage is the effectiveness of the random evolution approach. This strategy scores best among the ones considered in the present study. An interesting difference lies in the sub-optimal strategies that score high in for the medium voltage network and the low voltage network evolution. For the medium voltage network, it is best to provide more connectivity between those nodes that already hold a high node degree, thus reinforcing their role as key components of the network. On the other hand, for the low voltage network, it seems that adding more connectivity between the nodes that have a small connectivity provides better performance in the evolution. The assortative low degree aims at creating more connections and (therefore hubs) where there is less connectivity in the current samples. Also the other strategy that is sub-optimal for low voltage networks, the dissortative, aims at giving a more important role to the nodes in the periphery of the network by connecting them to the more connected nodes. A synthesis of the topological performance of the different strategies is provided in Table 4. For the layer of the power grid considered (column one), each strategy (column two) is assessed with an optimality level (column three) based on the satisfaction of the topological metrics. The step during the evolution process in which the most of the metrics are satisfied is also provided in column four. The achievement of the good results depends on the network layer and on the strategy used. The optimality level is assigned based on the full satisfaction of the topological metrics by the all samples described earlier in this section and more thoroughly in 4.1. One can see a distinction between the medium voltage and the low voltage networks: the low voltage achieve less topological optimality (less metrics are satisfied) although requiring on average more evolution steps. Another aspect to note is that some evolution strategies (i.e., assortative high degree and triangle closure) do not have an improvement between the various steps despite the addition of more connectivity. On the other hand, other strategies (i.e., dissortative and random) benefit more from additional connectivity by improving the satisfaction of the metrics.

The above conclusions are reached purely based on topological considerations. When also the costs of the evolution are taken into account, the optimal strategy might be different. The extended analysis that consider economic aspects is presented next.

5. Economic considerations

Traditionally the problem of evaluating the expansion of an electrical system is a complex task that involves both the use of modeling, usually based on operation research optimization techniques and linear programming [22], and the experience and vision of experts in the field aided by computer technologies [23]. In this latter case, computers acquire knowledge based on previous expert decision and, based on the electrical physical constraints of the domain, are then able to support power grid evolution decision finding the most suitable technical and economical solution [24]. With more distributed generating facilities in the distribution network, traditional methods have limits and need to be modified or updated to take into account the new scenarios of the Smart grid. The strategies that we have so far analyzed as being candidates for evolving the current grid in the future smart grid need also to be evaluated from the economic point of view. How much will it cost to deploy electrical infrastructures according to these models? What is the actual cost of adding an edge to the topology of the grid, physically?

To answer these questions, we characterize the cables used for the upgrading process in terms of their physical properties and costs. For the majority of the nodes in the samples belonging to the medium voltage, we know the geographical coordinate information, so with some approximation it is possible to compute the length of the new cable connecting nodes that do not have a line connecting them yet. Therefore, each newly added line is assigned a length. In order to define the properties characterizing the new cables, we adopt a k-nearest neighbor (KNN) classification based on the length

of the cable [25]. The classification is performed using the Java Machine Learning Library (Java-ML) v0.1.5 (<http://java-ml.sourceforge.net/>). For each new cable, we consider the k cables (we choose $k = 5$) in the original network, used as the training set for the classifier, that have the length closer to the added one and then the type of cable is available. We choose this method to identify the cable since it is simple and it has proven successful in several practical contexts [26]. Once the properties of the new cables are identified, all the information we need for the economic analysis are then available: resistance per unit of length, cost per unit of length, maximal supported current. We remark that our proposed analysis does not aim at being a comprehensive investment analysis, for which other techniques are well established [27], simply an economic evaluation of the proposed evolution strategies to confirm their feasibility or unfeasibility.

Once again, as in our previous work [3], to assess these costs in the medium voltage infrastructure, we consider a simple relation where the cost of cabling and cost of substations are added:

$$C_{impl} = \sum_{j=1}^N Ssc_j + \sum_{i=1}^M Cc_i \quad (1)$$

where C_{impl} stands for implementation cost, Ssc_j is the adaptation cost for the substation j and Cc_i is the cost for the cable i . The cost of the cable can be expressed as the sum of a term that takes into account the specific installation of cable i and a linear function considering the distance the cable i covers: $Cc_i = C_{inst_i} + C_{uc_i} \cdot l_i$. The term C_{inst_i} takes into account the specific costs arising in the installation of cable i given the topography/orography of the piece of land where the cable is installed. C_{uc_i} is the cable cost per unit of length and l_i is the length of the cable. There are several types of cables used for power transmission and distribution with varying physical characteristics and costs. In addition, a very important issue is the cost for installation. It can vary significantly based on the topography/orography of the land where the cables are installed [28]. In the present work, to provide an initial estimate, we simply consider cabling costs and ignore installation costs for cables. The case study of our work is on a relatively topographically/orographically easy piece of land such as the Netherlands. Therefore, in the case of the Netherlands we consider length a good proxy for the assessment of the cost of cabling. In addition, the cost related to the substations are ignored since they too dependent on other factors (e.g., equipment present in the substation) to be useful in the present analysis.

For the cost analysis, we limit our investigation to the three strategies that have scored best in the pure topological analysis, that is, random, assortative high node degree and least distance. For the medium voltage network, the most interesting result is the difference in the cost that the three methods of evolution require. On average the costs of network improvement is similar when considering the assortative and the random strategy: the cost of adding more edges is about 75% of the cost for cabling of the whole grid infrastructure. The situation is radically different for the least distance strategy whose development impacts only marginally in the total cost of the infrastructure, by adding just less than 13% of the cost of the infrastructure. Purely from the point of view of cabling costs, the most promising evolution strategy in economic and topological terms for the medium voltage grid is the strategy that connects the nodes that are geographically closer (i.e., least distance strategy).

One may then wonder if such investments are beneficial for the end -users and the distribution companies in reducing the cost of electricity flows. We resort to a set of metrics that we have developed and already applied to the Northern Netherlands distribution grid [2] and to synthetically generated networks [3]. The goal is to consider, from a topological perspective, those measures that are critical in contributing to the cost of electricity as elements in the Transmission and Distribution Networks as described in economic studies such as the one of Harris and Munasinghe [29,30]:

- losses both in line and at transformer stations,
- security and capacity factors,
- line redundancy, and
- power transfer limits.

For each of these elements we associate topological quantities that are representative, so that we can assess their values and therefore compare them in the original networks and in the evolutions as proposed here. In particular, we assess:

- Losses on the transmission/distribution line can be expressed by the quotient of the weighted characteristic path length:

$$WCPL_N. \quad (2)$$

- The average resistance of a line (a weighted edge in the graph):

$$\bar{w} = \frac{1}{M} \sum_{i=1}^M w_i. \quad (3)$$

- Losses at substation level are expressed as the number of nodes (on average) that are traversed when computing the weighted shortest path between all the nodes in the network:

$$L_{substation_N} = \overline{Nodes_{WCPL_N}} \quad (4)$$

- Robustness is evaluated with random removal strategy and the weighted-node-degree-based removal by computing the average of the order of maximal connected component between the two situations when the 20% of the nodes of the original graph are removed. It can be written as:

$$Rob_N = \frac{|MCC_{Random20\%}| + |MCC_{NodeDegree20\%}|}{2}. \quad (5)$$

- Redundancy is evaluated by covering a random sample of the nodes in the network (40% of the nodes whose half represents source nodes and the other half represents destination nodes) and computing for each source and destination pair the first ten shortest paths of increasing length. If there are less than ten paths available, the worst case path between the two nodes is considered. To have a measure of how these resilient paths have an increment in transportation cost, a normalization with the weighted characteristic path length is performed. We formalized it as:

$$Red_N = \frac{\sum_{i \in Sources, j \in Sinks} SP_{w_{ij}}}{WCPL}. \quad (6)$$

- Network capacity is considered as the value of the weighted characteristic path length, whose weights are the maximal operating current supported:

$$Cap_N = WCPL_{current} \cdot N. \quad (7)$$

- The average supported current of a line (a weighted edge in the graph):

$$\overline{w_{current}} = \frac{1}{M} \sum_{i=1}^M w_{icurrent}. \quad (8)$$

The aspects considered are just some of the factors (the ones closely coupled to topology) that influence the overall price of electricity. Naturally, there are other factors, e.g., fuel prices, government strategies and taxation, as illustrated for instance in the economic studies of Harris and Munasinghe [29,30].

To give a general idea of the improvement, we use the average results over the 12 medium voltage networks samples. For each strategy, we look at the improvement, in percentage, for the same metrics compared to the initial samples. Already from a small increase in connectivity (addition of 25% of edges) the resistance of a path decreases with every strategy with the best result obtained by the assortative high degree strategy. Adding more lines in general promotes a reduction of the average resistance of edges compared to the initial situation. This is even more true in the assortative and least distance strategy where short distance connections (and therefore less resistive) tend to dominate or more efficient cables are chosen in the KNN procedure selection. In addition, a considerable reduction in the losses that are experienced in traversing substation can be avoided with more dense networks: almost 30% less stations traversed in the graph enhanced with assortative connections; of course less benefits take place with the least distance strategy that reduces the average number of traversed stations in a path by 7%. This higher connectivity provides benefits to the robustness aspects: alternative paths that are less lossy (about 30% reduction for the least distance strategy). An improvement is also experienced in the resilience of the network to node disruptions: about 80% more resilience with the random strategy. Also the amount of current that is supported in a path (the weighted characteristic path length with maximal supported current as weight of the edges) is definitely higher (more than 2.5 times for the least distance strategy) compared to the initial samples. Similar considerations can be done for the second evolution step (i.e., +50% cables). Considering the loss aspect the benefits are for the three strategies on average about 30% in the reduction of the weighted path. For the average weight (i.e., resistance) of a cable the random addition creates networks with much more cables with a high resistance. This is an indication that the random strategy creates long distance connections that act as shortcuts in the network from a topological point of view. However, in a physical system there are no significant benefits since the resistance grows with the distance. These limits of the benefits are shown by the weighted path analysis. Considering robustness oriented metrics, the most of the benefits take place in resilience where the networks on average stay twice as much as connected than the initial evolution step, except for the assortative strategy that lags behind. A small decrease for all the strategies in the characteristic path is noticeable when the weight is the maximal current that can flow in the cables; this is not difficult to understand since the characteristic path uses the most efficient one (i.e., with smallest weight paths). When even more connectivity (+75% and +100%) is added, one sees even better results and improvements but smaller in their magnitude. In these last two stages, the benefits for the losses reach values of reduction above 30%, the same for the nodes to be traversed on average on a path. Only the least distance strategy has a small reduction, but this is due to the very nature of such evolution strategy that avoids long distance (topological shortcuts) cables. Considering network robustness, the main improvements are for resilience to node failures that for the least distance strategy allow the network to be twice as much as robust than the initial samples. Concerning the capacity of the network we assist to a slight decrease for the same reasons that we have explained above. However, the networks with the least distance evolution are able on average to transport twice the amount of current than the initial samples.

Given the cost analysis for cable addition and the benefits that such an higher connectivity brings to the networks considering the different strategies in the topological aspects related to price of electricity, we provide a suggestion on

how to evolve the analyzed samples. Using our topological-based method, we consider that the least distance strategy with the addition of 75% or 100% of edges is a very good way of making the network more connected. Such an evolution strategy provides benefits from a topological point of view, and it keeps the costs low. For the samples examined it requires an investment in cabling costs about 25% of the value of the cables already on the ground. Such investment can provide benefits in the loss reduction of the network as well as in its robustness. The energy economic studies show [29,30] that losses and robustness are directly related to the cost of electricity. These factors are tight to topological parameters, as shown above, therefore such evolution would provide less cost in electricity distribution. It is difficult to translate in exact monetary terms for the end-user the savings in the energy bill that an improvement in the distribution topology might bring. For the realization of a smart grid less costs in the distribution of electricity and a local reliable and robust network are the essential ingredients to enable a paradigm where energy is produced and distributed locally such as at neighborhood or city level. The present economic analysis based on the changes of topology of the distribution grid suggests a reduction on the price of electricity. However other dynamics might take place in the actual implementation of the suggested action that might actually force the price of electricity distribution to increase. For instance a requirement of the distribution utility companies to return rapidly from the investment made. This factor influences the prices to increase at least in the short term.

6. Related work

To the best of our knowledge there are no works that use the principles of complex network analysis to design and consider evolutions of distribution grid networks. Thus, in considering related work, we look into three main related areas: Evolution of complex networks, complex network analysis studies applied to the power grid, and electrical engineering power lines design and adaptation.

Evolution of complex networks

The problem of the evolution of networks looked through the glasses of complex network analysis has been widely investigated. The focus is mainly to assess and analyze existing networks that have evolved over time and understand which principles and patterns underlie such evolution. More in general, the evolution of networks is considered in defining abstract algorithms that can be used to build networks that mimic the same behavior of natural or synthetic networks. The work of Liben-Nowell and Kleinberg [31] discusses link prediction. The authors consider the evolution of the ArXiv library co-authorship network (i.e., a social network) and define several quantitative metrics to infer the future links to be formed in the network (i.e., new co-authored publications). The metrics that the authors use for predictions are based on evaluating the paths, the neighborhood of nodes, rank of the matrix representing the graph, and clustering. The metrics used in the prediction of new connections between nodes prove valuable for the co-authorship social network. Even if at abstract level networks are the same (i.e., graphs), it is difficult to apply these metrics and prediction strategies in a real infrastructure such as the power grid. In fact, many of the metrics considered in the paper are inspired by the underlying social aspects of the co-author relationship such as neighbors in common. Given the small average node degree of the power grid networks, the absence of samples at different time stamps, it is difficult to apply the metrics and methods of the paper to Distribution Networks and expect meaningful and interesting results.

The importance of considering how the nodes with similar degree are connected and how the effects of propagation of events (e.g., failures, contagion) in a network spread are analyzed in Ref. [32]. The assortativity or disassortativity rewiring process of links in networks lead to a drastic change in the evolution of the diffusion process involving the network: a more assortative network increases the probability of a global contagion on the one hand, while decreasing the speed of the diffusion on the other. When looking at the power grid however one must take into account that the dynamics of the process on top of the networks has to satisfy the constraints of the components and obey the Kirchhoff Laws.

The survey of Lü et al. [33] provides a good overview on link prediction. The authors propose several methods and algorithms based on similarity properties of the nodes at local level (e.g., the neighborhood of a node), global similarity (i.e., over the whole network), and quasi-local level that combines the best of the two approaches. They also propose other strategies such as probabilistic models to evaluate the likelihood of the formation of a link. One of the networks that is considered for link prediction in Ref. [33] is the Western US power grid. In this case, the methods that favor local interactions between nodes perform better in the prediction than other approaches. The authors also state that for the infrastructural networks, geography plays an important role where long distant connections are discouraged and very rare. We consider these prediction mechanisms valuable for networks with rich neighborhood structures where differences and intersection between neighborhoods are meaningful (e.g., social networks) or where the discovery of links is particularly costly or long in time and efforts (e.g., protein interactions). The current power grid networks have low average node degree and the structure is usually close to radial, especially at medium and low voltage level, thus we consider the predictions less interesting. However, these techniques and link predictions might be more applicable in the further evolution and prediction of new links when the networks are more rich in connectivity. In addition, some techniques for link prediction would benefit from additional information available to characterize the nodes, i.e., the number of prosumers that are connected to a node (i.e., substation) and the available production power.

Complex network approach to the power grid

Complex Network Analysis works take into account the power grid at the high voltage level usually to analyze the structure of the network without considering in detail the physical properties of the power lines. In our previous work [4], we analyzed the main scientific papers that investigate power grid properties using the complex network analysis approach. There are two main categories of motivations: (1) understanding the intrinsic property of grid topologies and compare them to other types of networks assessing the existence of properties such as small-world or scale-free [34,14]; (2) better understanding the behavior of the network when failures occur (i.e., edge or node removal) and analyze the topological causes that bring to black-out spread and cascading failures of power lines [35]. Few studies in the complex network analysis landscape consider the possibility of using the insight gained through the analysis to help the design in terms of the reliability of the power grid. Examples are the study of the Italian high voltage grid [36] and the study of improvement by line addition in Italian, French and Spanish Grids [37]. Also Holmgren [38] uses the complex network analysis to understand which grid improvement strategies are most beneficial showing the different improvement of typical complex network analysis metrics (e.g., path length, average degree, clustering coefficient, network connectivity) although in a very simple small graph (less than 10 nodes) when different edges and nodes are added to the network. Concerning the topic of smart grid with focus on the high voltage network, Wang et al. [39] study the power grid to understand the kind of communication system needed to support the decentralized control required by the new power grid applying complex network analysis techniques. The analyses aim at generating samples using random topologies based on uniform and Poisson probability distributions and a random topology with small-world network features. The simulation results are compared to the real samples of US power grid and synthetic reference models belonging to the IEEE literature. These works also investigate the property of the physical impedance to assign to the generated grid samples.

A recent proposal that could be applied in the smart grid context is presented in Ref. [40]. The paper gives an algorithm for the activation of back-up links present in a network that have to become available after a failure, in order to re-establish the connectivity properties. This idea will be valuable for smart infrastructures. The topologies analyzed are planar square grids, preferential attachment networks (i.e., Barabasi–Albert model), and Watts–Strogatz small-world networks. The topology that better performs in tolerating random failures is the preferential attachment one, however it is difficult to realize in a real physically constrained infrastructure; therefore, the best result are achievable in the real world by the small-world model. The paper, does not provide an economic analysis to consider the cost of the implementation of the proposed redundant link structure.

Power engineering approach for power lines design and adaptation

A power engineering problem that resembles our present proposal is that of distribution grid topological reconfiguration. The early works on the topic of Merlin and Back [41] considered the problem with heuristic techniques and algorithms (e.g., branch and bound) to reconfigure the switches of the distribution infrastructure. Later works of Civanlar et al. [42] provide computationally tractable methods to modify the topology of the distribution grid by opening/closing switches to reduce losses. The authors provide a simplified formula to estimate the reduction in losses between the situation before and after the reconfiguration in the topology.

More recently, with the new interest in the distribution grid due to the smart grid and distributed generation opportunities to be placed in the distribution layer of the power grid, the reconfiguration problem together with islanded grids and micro-generation plants has raised increasing attention. The work of Ramesh et al. [43] focuses on the minimization of losses in the distribution grid. The authors provide several options that have been simulated and tested on the field to reduce losses on real and reactive power. The three solutions proposed concern three areas: distributed generation, capacitor placement and restructuring of feeders. The third proposed technique concerns the restructuring of the topology of the network. This last aspect is closer to the topic of the current paper. The solution proposed in Ref. [43] is basically a reconfiguration of the opening and closing of the switches of the distribution network to maintain the network radial and satisfy its load requirements. This approach although valuable from the practical point of view, lacks the vision in imagining the future energy scenario and there is no investigation of which topology is best, or according which principles the new pieces of infrastructure (e.g., cables) should be interconnected.

Power system engineers do resort to graph theory principles [44], though CNA is not typically considered as a design tool. The traditional techniques involve the individuation of an objective function representing the cost of the power flow along a certain line which is then subject to physical and energy balance. This problem translates in an operation research problem. These models are applied both for the high voltage planning [45] and the medium and low voltage [44] since long time. The same consideration regarding the need of a different approach in planning in a deregulated market are expressed in Ref. [46] where an optimization of an objective function in the market environment is applied.

7. Conclusions

The smart grid promises to revolutionize the energy sector providing the grid with more efficiency, real-time information and renewable power sources penetration. In such vision, the end-users will be able to produce their own energy and exchange the surplus in a completely free market. Based on the experience that we accrued in our previous study of

distribution grid evolution considering complex network models, we went forward considering several types of possible evolution of existing networks by increasing connectivity. We used physical samples from the Distribution grid of the Northern Netherlands and we have applied six distinct strategies. We performed two types of analysis of the results. First, a pure topological analysis considering a set of specifically defined metrics where random evolution, assortative high degree and least distance evolution strategies resulted as best satisfying the desiderata of the metrics. In our second set of analysis, we also took into account the physical properties of the cables, therefore realizing a weighted graph analysis, and considering the cost of evolving the networks assessing the cost of cables. In this weighted analysis, we have seen that the random and assortative high degree are the best strategies in a pure topological analysis, but they have costs that are extremely high and unrealistic to realize in practice. In addition, the weighted analysis gave us the possibility to investigate the elements of the power grid that influence the cost of electricity distribution (i.e., grid losses and grid reliability) and the results of this analysis suggest that evolving the network by adding connections between the nodes with smallest distance is beneficial and provides in many cases better results compared to the other evolution strategies. Therefore, with an investment about 25% of the actual costs in cables already on the ground the distribution grid can improve consistently in reducing transportation costs. The results obtained here are focused on few samples belonging to the distribution grid of the Northern Netherlands. The strategies that are successful in these samples might not be the same when other topologies belonging to different countries and geographical regions are considered. Rather than focusing on just one single strategy, a mixing of strategies might be used to obtain a better result: sub-sections of the network could benefit from a strategy, while other sections might have a maximization of the performance with another way of adding the connectivity. A dynamic approach considering different strategies to network connections wiring and removal of nodes has been considered in Ref. [47] where the strategies are driven by a genetic algorithm optimization approach. A similar approach could be applied for the power infrastructure as well. We consider this material for follow-up research.

Acknowledgments

The work is supported by the Dutch National Research Council under the NWO Smart Energy Systems programme, contract no. 647.000.004. Pagani is supported by University of Groningen with the Ubbo Emmius Fellowship 2009 and IBM Ph.D. Fellowship 2013–14.

References

- [1] M.G. Morgan, J. Apt, L.B. Lave, M.D. Ilic, M. Sirbu, J.M. Peha, The many meanings of “Smart Grid”, Technical Report, Carnegie Mellon University, 2009.
- [2] G.A. Pagani, M. Aiello, Towards decentralization: A topological investigation of the medium and low voltage grids, *IEEE Trans. Smart Grid* 2 (2011) 538–547.
- [3] G.A. Pagani, M. Aiello, Power grid complex network evolutions for the smart grid, *Physica A* 396 (2014) 248–266.
- [4] G.A. Pagani, M. Aiello, The power grid as a complex network: A survey, *Physica A* 392 (2013) 2688–2700.
- [5] U.S. Dept. of Energy, “Grid 2030” A National Vision For Electricity’s Second 100 Years, Technical Report, U.S. Dept. of Energy, 2007.
- [6] M. Wissner, The smart grid—a saucerful of secrets? *Appl. Energy* 88 (2011) 2509–2518.
- [7] J.P. Lopes, N. Hatziaargyriou, J. Mutale, P. Djapic, N. Jenkins, Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities, *Electr. Power Syst. Res.* 77 (2007) 1189–1203.
- [8] R. Cossent, T. Gómez, P. Frías, Towards a future with large penetration of distributed generation: Is the current regulation of electricity distribution ready? regulatory recommendations under a European perspective, *Energy Policy* 37 (2009) 1145–1155.
- [9] V.V. Vaitheeswaran, Power to the People: How the Coming Energy Revolution Will Transform an Industry, Change Our Lives, and Maybe Even Save the Planet, Earthscan, 2005.
- [10] T.L. Friedman, Hot, Flat, and Crowded: Why We Need a Green Revolution—and How It Can Renew America, Picador, 2008.
- [11] R. Brown, Impact of smart grid on distribution system design, in: Power and Energy Society General Meeting—Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE, pp. 1–4.
- [12] P. Erdős, A. Rényi, On Random Graphs. I, *Publ. Math. Debrecen* 6 (1959) 290–297.
- [13] M. Newman, A.-L. Barabási, D.J. Watts, The Structure and Dynamics of Networks, Princeton University Press, 2006.
- [14] D.J. Watts, Small Worlds: The Dynamics of Networks between Order and Randomness, Princeton Univ. Press, Princeton, NJ, USA, 2003.
- [15] M.E.J. Newman, Networks: An Introduction, OUP Oxford, 2010.
- [16] M.E.J. Newman, Assortative mixing in networks, *Phys. Rev. Lett.* 89 (2002) 208701.
- [17] U. Brandes, A faster algorithm for betweenness centrality, *J. Math. Sociol.* 25 (2001) 163–177.
- [18] D.J. Watts, S.H. Strogatz, Collective dynamics of ‘small-world’ networks, *Nature* 393 (1998) 440–442.
- [19] A. Vázquez, R. Pastor-Satorras, A. Vespignani, Large-scale topological and dynamical properties of the Internet, *Phys. Rev. E* 65 (2002) 1–12.
- [20] R. Cohen, K. Erez, D. Ben-Avraham, S. Havlin, Resilience of the Internet to random breakdowns, *Phys. Rev. Lett.* 85 (2000) 4626–4628.
- [21] M. Rosas-Casals, B. Corominas-Murtra, Assessing European power grid reliability by means of topological measures, Work Paper, 2009.
- [22] L. Garver, Transmission network estimation using linear programming, *IEEE Trans. Power Appar. Syst.* PAS-89 (1970) 1688–1697.
- [23] L.L. Grigsby (Ed.), The Electric Power Engineering Handbook, Second ed., CRC Press, 2007.
- [24] R. Teive, E. Silva, L. Fonseca, A cooperative expert system for transmission expansion planning of electrical power systems, *IEEE Trans. Power Syst.* 13 (1998) 636–642.
- [25] T. Cover, P. Hart, Nearest neighbor pattern classification, *IEEE Trans. Inform. Theory* 13 (1967) 21–27.
- [26] G. Shakhnarovich, T. Darrell, P. Indyk, Nearest-Neighbor Methods in Learning and Vision: Theory and Practice (Neural Information Processing), The MIT Press, 2006.
- [27] F.J. Stermole, J.M. Stermole, Economic Evaluation and Investment Decision Methods, Investment Evaluations Corporation, 2009.
- [28] National Grid, Undergrounding high voltage electricity transmission—The technical issues, Technical Report, National Grid, 2009.
- [29] C. Harris, Electricity Markets: Pricing, Structures and Economics, Wiley, 2006.
- [30] M. Munasinghe, Engineering-economic analysis of electric power systems, *Proc. IEEE* 72 (1984) 424–461.
- [31] D. Liben-Nowell, J. Kleinberg, The link-prediction problem for social networks, *J. Am. Soc. Inf. Sci. Technol.* 58 (2007) 1019–1031.
- [32] G. D’Agostino, A. Scala, V. Zlatić, G. Caldarelli, Robustness and assortativity for diffusion-like processes in scale-free networks, *Europhys. Lett.* 97 (2012) 68006.
- [33] L. Lü, T. Zhou, Link prediction in complex networks: A survey, *Physica A* 390 (2011) 1150–1170.

- [34] L.A.N. Amaral, A. Scala, M. Barthélemy, H.E. Stanley, Classes of small-world networks, *Proc. Natl. Acad. Sci. USA* 97 (2000) 11149–11152.
- [35] R. Albert, I. Albert, G. Nakarado, Structural vulnerability of the north American power grid, *Phys. Rev. E* 69 (2004).
- [36] P. Crucitti, V. Latora, M. Marchiori, Locating critical lines in high-voltage electrical power grids, *Fluct. Noise Lett.* 5 (2005) L201–L208.
- [37] V. Rosato, S. Bologna, F. Tiriticco, Topological properties of high-voltage electrical transmission networks, *Electr. Power Syst. Res.* 77 (2007) 99–105.
- [38] A.J. Holmgren, Using graph models to analyze the vulnerability of power networks, *Risk Anal.* 26 (2006) 955–969.
- [39] Z. Wang, A. Scaglione, R.J. Thomas, Generating statistically correct random topologies for testing smart grid communication and control networks, *IEEE Trans. Smart Grid* 1 (2010) 28–39.
- [40] W. Quattrocioni, G. Caldarelli, A. Scala, Self-healing networks: Redundancy and structure, *PLoS One* 9 (2014) e87986.
- [41] A. Merlin, H. Back, Search for a minimal-loss operating spanning tree configuration in an urban power distribution system, in: *Proc. of the Fifth Power System Conference, PSCC, Cambridge*, pp. 1–18.
- [42] S. Civanlar, J. Grainger, H. Yin, S. Lee, Distribution feeder reconfiguration for loss reduction, *IEEE Trans. Power Deliv.* 3 (1988) 1217–1223.
- [43] L. Ramesh, S.P. Chowdhury, S. Chowdhury, A.A. Natarajan, C.T. Gaunt, Minimization of power loss in distribution networks by different techniques, *Int. J. Electr. Power Energy Syst. Eng.* 3 (2009).
- [44] D. Crawford, S.B. Holt, A mathematical optimization technique for locating and sizing distribution substations, and deriving their optimal service areas, *IEEE Trans. Power Appar. Syst.* 94 (1975) 230–235.
- [45] S. Lee, K. Hicks, E. Hnyiliczka, Transmission expansion by branch-and-bound integer programming with optimal cost–capacity curves, *IEEE Trans. Power Appar. Syst.* PAS-93 (1974) 1390–1400.
- [46] H. Shariati, H. Askarian Abyaneh, M. Javidi, F. Razavi, Transmission expansion planning considering security cost under market environment, in: *Electric Utility Deregulation and Restructuring and Power Technologies, 2008. DRPT 2008. Third International Conference on*, pp. 1430–1435.
- [47] H. Arnold, D. Masad, G.A. Pagani, J. Schmidt, E. Stepanova, Network disruption and recovery: Co-evolution of defender and attacker in a dynamic game, in: P. Contucci, R. Menezes, A. Omicini, J. Poncela-Casasnovas (Eds.), *Complex Networks V*, in: *Studies in Computational Intelligence*, vol. 549, Springer International Publishing, 2014, pp. 141–155.